

Method and system for controlling a heat pump

1. Technical field

5 The present disclosure relates to a method, an apparatus, a system and a computer program for controlling a heat pump that may provide process heat and/or process cooling for food processing plants, such as spray dryers or similar applications.

2. Technical background

Heat pumps provide process heating and / or process cooling for a great variety of industrial and domestic applications at high efficiency.

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The working principle of heat pumps, such as mechanical vapor-compression heat pumps, is based on expansion, heat absorption, pressurization and heat release of a process medium, such as carbon dioxide, CO₂. The process medium absorbs heat (while being at a low pressure) at a supplier side (heat source side) of the heat pump. Thereby, 15 the process medium may evaporate. At a consumer side (heat sink side) of the heat pump, the process medium may release heat. When releasing heat, the process medium is at a higher pressure than at the heat source side. Thereby, the process medium may condensate. This applies for subcritical heat pumps. In case of transcritical heat pumps, the process medium may cool substantially without a phase change. Heat pumps 20 usually employ a compressor and a throttling valve to facilitate pressure change of the process medium.

Heat pumps require a control method, e.g. for controlling a desired target temperature at a consumer side of the heat pump, e.g., via adjusting the heat pump's capacity. This 25 may be achieved via a change of the compressor's absorbed power in response to a varying temperature.

However, conventional heat pump control methods and systems have various deficiencies. For instance, conventional control methods may exhibit control

instabilities and/or insufficient control bandwidth. Furthermore, conventional control methods may require a buffer tank or similar equipment to compensate for unstable conditions, e.g., via decoupling a heat pump heat generation from the consumer side heat demand etc. This requires increased installation space and is detrimental in terms of efficiency. In addition, conventional heat pumps are often controlled in a manner that the heat pump does not operate at optimum performance. This increases the power required for operating the heat pump, resulting in increased operational expenditures and, potentially, causes an increased carbon footprint. For example in conventional control methods, typically, the internal operating conditions of the heat pump, such as the compressor power may vary significantly. This may adversely affect the performance, as the heat pump cannot be operated at optimum efficiency.

Further, some conventional heat pump control methods cannot control temperatures on the hot side and on the cold side of a heat pump at the same time in a sufficiently stable manner. In this general context, US 2002/0134095 A1 relates to a refrigerator that includes a first passage including a cold storage zone capillary tube and a cold storage zone evaporator, the latter two being connected in series to each other, a second passage including a freezing zone capillary tube and a freezing zone evaporator, the latter two being connected in series to each other, a switching valve causing the refrigerant condensed by the condenser to flow selectively through any one of the first passage, the second passage and both the first and second passages, a variable speed, cold storage zone fan circulating air in the cold storage zone while the air is in contact with the cold storage zone evaporator, a variable speed, freezing zone fan circulating air in the freezing zone while the air is in contact with the freezing are evaporator, and a control device switching the switching valve upon power supply to the refrigerator so that the refrigerant flows simultaneously through both the first and second passages.

Further, US 7,316,267 B2 relates to a flash water heater using a heat pump that includes a heat exchanger in which a refrigerant flow path exchanges heat with a water flow path. Tap water is led directly to the water flow path, and hot water supplied from the water flow path is used. The water heater includes at least one of the following elements: 1) a load setter for setting a heating amount in the heat exchanger, and a heating controller for regulating a heating amount in response to an amount set by the load setter; 2) a heater for heating water flowing through the water flow path in the

heat exchanger and water flowing the path before and after the heat exchanger; 3) plural compressors; and 4) plural heat-pump cycles. The water heater is excellent in start-up of hot water temperature when the hot water supply starts, controllability, and efficiency.

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Further, US2014060092A1 relates to a method of operating a heat pump dryer, the heat pump dryer including a process air circuit and a heat pump unit having a refrigerant evaporator for cooling process air, a primary refrigerant condenser for heating process air, an auxiliary refrigerant evaporator arranged outside the process air circuit and connected between the primary refrigerant evaporator and a compressor of the heat pump unit, and at least one auxiliary fan adapted to impinge an air stream at the auxiliary heat exchanger.

In view of the foregoing, there is a need to provide improved control methods for heat pumps. In particular, aspects of the present disclosure are directed to improve various deficiencies of the prior art outlined above.

3. Summary

These and other objects are solved at least partially by the subject-matter of the independent claims. Optional embodiments are subject of the dependent claims.

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An aspect of the present disclosure relates to a method for controlling a heat flow of a heat pump, the method comprising: measuring an output parameter associated with an amount of process heat provided by the heat pump to a consumer, and controlling, based on the measured output parameter, an amount of input heat provided to the heat pump.

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As an example, the heat flow may refer to an amount of heat absorbed by the heat pump from a heat reservoir and / or from one or more heat suppliers and supplied (per unit of time) to one or more consumers as usable process heat.

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The process heat may be used by the consumer for any kind of heating purpose, e.g., for drying food, heating of a building and/or district heating. The output parameter may

for example be a temperature and / or a volume flow rate of a process medium, like water, air or oil, etc.

For example, the input heat may be associated with a cold side or input side of the heat pump, operated at a temperature at which a process medium (e.g. a refrigerant like CO₂) of the heat pump usually evaporates and thereby absorbs heat from a heat reservoir or a heat supplier such as a piece of equipment cooled by the heat pump. The process heat provided by the heat pump may be associated with a hot side or output side of the heat pump, operated at a temperature at which the process medium of the heat pump usually cools down and releases heat to an output fluid of the heat pump. In case of subcritical heat pumps, the process medium usually cools down and condenses, thereby also releasing heat to an output fluid of the heat pump.

It is important to note that controlling the amount of input heat provided to the heat pump is not the same as controlling the operation of the heat pump itself, e.g., via changing the power level of the compressor. For example, changing the compressor power at a given input heat flow to the heat pump changes which part e.g., which percentage of the input heat provided to the heat pump is actually absorbed by the process medium of the heat pump. By contrast, changing the amount of input heat does not directly affect the internal operation of the heat pump but amounts to controlling the operational environment of the heat pump, e.g., via increasing the temperature and / or the volume flow rate of a heat reservoir fluid provided to the input side / cold side of the heat pump. Aspects of the present disclosure thus facilitate a more stable, efficient and/or robust operation of the heat pump. For example, in this manner, a desired output characteristic of the heat pump, such as a set output temperature may be reached faster and/or with less fluctuations as compared to conventional implementations, where for example only the compressor power is changed in response to a changed output temperature setpoint. The method has the additional advantage that a demanded amount of process heat (at a specified temperature) can be provided whilst simultaneously providing process cooling (at a specified temperature) by varying the input heat. This can be performed in a stable manner.

Further, aspects of the present disclosure thereby allow that the heat pump may remain at stable operating condition even if the output temperature or amount of heat required

changes. For instance, in this manner, the heat pump, e.g., the compressor, may be operated at preferable operation conditions, e.g., at a point of high efficiency, over a wide range of output characteristics.

5 Depending on the field of application of the aspects described herein, the controlling may advantageously cope with varying temperature levels of suppliers or process cooling consumers providing the amount of heat input to the heat pump.

10 Preferably, in the method, controlling the amount of input heat provided to the heat pump comprises controlling a temperature and/or a flow rate of an input fluid providing the input heat to the heat pump.

Such heat supplies could be components, devices and/or units that are cooled by the heat pump and which provide residual and/or waste heat.

15 It is appreciated that both, a temperature, and a flow rate of an input fluid can be controlled. In a preferred embodiment, the flow rate of the input fluid may be constant, and the temperature of the input fluid is controlled. This has the advantage that the velocity of the input fluid does not substantially vary, which means that pipe
20 dimensions for the input fluid may be designed to improve fluid dynamic performance. This may allow for optimum design of components, such as pipes (guiding the input fluid), heat exchangers and the like.

25 In some aspects, the measured output parameter comprises one or more of the following: an output energy flow, an output power, an output mass flow, an output temperature, an output volume flow, and an output flow velocity associated with an output fluid provided by the heat pump.

30 The output fluid may be the output fluid of the hot side of the heat pump and may be provided with one or more consumers in a fluid cycle separate to a fluid cycle of the process medium of the heat pump. The consumers could be components, devices and/or units requiring process heat. The skilled person understands, that when reference is made to a mass flow, volume flow or the like, it may be understood as the

mass flow rate, volume flow rate or the like. Thus, herein, a mass flow/mass flow rate indicates an amount of mass of a substance per unit time, i.e. in SI units [kg/s].

5 The measured output parameter may be suitably selected, such that determining the amount of process heat is facilitated. Preferably the measured output parameter is a parameter that can be easily measured. Measuring may be performed by way of a sensor. If the measured output parameter is a temperature, common examples of the sensor may be a thermocouple or a resistance temperature detector (RTD). The temperature measurement may be performed with the help of an electrical signal
10 method. The means for measuring the output parameter may be placed within or in proximity of the output fluid of the heat pump.

A flow rate, a density or similar parameters of the output fluid may also be measured.

15 It is to be appreciated that the measured output parameter aids in determining or estimating the amount of process heat provided by the heat pump. For instance, if the mass flow, the heat capacity and a temperature of the output fluid are known, the amount of heat provided by the heat pump can be determined or estimated.

20 In some aspects, controlling the amount of input heat may comprise adjusting, preferably dynamically, a transfer function and/or a setpoint of a control loop controlling the amount of input heat.

For example, such a control loop could comprise sensing the temperature of an input
25 fluid providing the input heat to the heat pump, comparing the sensed temperature to a setpoint to obtain an error signal, and adjusting the temperature of the input fluid based on the error signal, e.g., via a P, PI or PID controller or using similar equipment that controls a mixing ratio of several fluids of different temperature.

30 Adjusting the transfer function and/or the setpoint of such a control loop controlling the amount of input heat has the advantage that the amount of input heat can be adjusted to varying output characteristics (e.g. when the output temperature or amount of heat required changes) in a stable and reliable manner with reduced fluctuations.

As an example, a consumer may demand more process heat, which may result in a drop of temperature of a fluid returned from a consumer to the heat pump. In some examples, even the outlet temperature of the heat pump may be affected. To compensate, aspects of the present disclosure adjust, e.g., increase, the setpoint of the control loop that is configured to control the amount of input heat. The setpoint may be a temperature setpoint. In this manner, the operation of the heat pump and in particular the temperature of the heating and the cooling provided by the heat pump may remain stable even in presence of large fluctuations of consumer demands.

A transfer function may model the control loop's output for each possible input and may comprise one or more constant or varying values associated with proportional, integral and/or differential elements of controllers. As an example, the transfer function may comprise a gain factor (as used for example for a proportional element of a controller).

In some aspects, the method discussed above may further comprise a step of: obtaining one or more of the following additional information: a temperature setpoint associated with the amount of process heat, a temperature setpoint associated with the amount of input heat, a thermal and optionally measured parameter associated with the amount of process heat, a thermal and optionally measured parameter associated with the amount of input heat, a setpoint of the heat pump, optionally a temperature setpoint of a process medium of the heat pump, an operational and optionally measured parameter of the heat pump, preferably the measured electrical power consumption of the heat pump, and a step of: controlling, based on the obtained additional information, the amount of input heat provided to the heat pump.

In some aspects, controlling the amount of input heat based on the obtained additional information may comprise the following: determining, based on the obtained additional information, an energy balance of the heat pump, predicting, based on the determined energy balance, an input parameter associated with the amount of input heat provided to the heat pump and controlling the amount of input heat based on the predicted input parameter.

For instance, the predicted input parameter could be used as a setpoint for a control loop controlling the amount of input heat.

5 An energy balance may comprise substantially all heat flows and powers crossing a boundary of a control volume corresponding to the heat pump. In particular, the energy balance may comprise process heat provided by the heat pump, input heat provided to the heat pump and power, such as power of compressors operating the heat pump.

10 The setpoint associated with the amount of input heat could be a temperature setpoint for the input fluid that provides the input heat to the heat pump.

The thermal and optionally measured parameter associated with the amount of process heat and / or the thermal and optionally measured parameter associated with the amount of input heat may comprise a heat capacity (e.g., an isobaric or isochoric heat capacity) or a mass flow or similar parameters.

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The obtained additional information may comprise a setpoint of the process medium (e.g. the refrigerant) of the heat pump. As an example, this setpoint could be a setpoint associated with the temperature of the refrigerant in an evaporator of the refrigerant cycle of the heat pump. Preferably, the setpoint is a setpoint for the suction pressure at saturated gas conditions. For instance, in such saturated gas conditions, the temperature is the temperature at which water vapor is preferably in thermodynamic equilibrium with its condensed state. As the pressure and temperature are physically related to one another, one can derive, by way of the saturated suction pressure, the temperature at saturated suction pressure. Thereby, the setpoint of the process medium referred to herein may also be a setpoint for the temperature at saturated suction pressure. This setpoint could thereby be associated with the amount of input heat provided to the heat pump, as the temperature/pressure at the exit of the evaporator of the refrigerant cycle may aid in determining the amount of input heat provided to the heat pump.

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An operational parameter of the heat pump may also comprise for instance a capacity, pressure ratio and/or efficiency of the compressor of the heat pump. A capacity of the compressor may be proportional to a flow rate of the compressor.

One or more parameters of the energy balance may be obtained as described herein (e.g. using measurements, obtaining setpoints or the like). The energy balance may for instance be used to predict an input parameter such as a temperature of an input fluid to the heat pump. This has the advantage that the predicted input parameter can be used for controlling the amount of input heat. In particular, this allows to improve said input parameter and/or to acknowledge parameters of the side of the process heat to derive an improved input parameter, which leads to reduced fluctuations (e.g., a fluctuation which could otherwise occur when a desired setpoint of a consumer receiving process heat is varied).

A particular advantage is that the energy balance comprises a combination of information related to future operating values corresponding to stable states the heat pump may tend to have, and actual operating values, e.g., the temperature setpoints can serve as a prediction for the next stable state, while the measured values correspond to the actual values.

The inventors found that the obtained additional information as well as the determination of the energy balance and the prediction of an input parameter as described herein are highly beneficial for controlling (and reducing fluctuations of) the heat pump heating side (hot supply temperature and/or heat amount) and cooling side (cold supply temperature), as most of the relevant parameters are considered.

For instance, the predicted input parameter may comprise a temperature of an input fluid providing the input heat to the heat pump.

This has the advantage that the predicted temperature of the input fluid can be used in the method for controlling a heat flow as described herein. This reduces fluctuations and facilitates a fast and robust response in controlling a heat flow of a heat pump.

Further, the method described herein may comprise adjusting the transfer function and/or the setpoint of the control loop controlling the amount of input heat based on the predicted input parameter.

This further improves controlling of the heat flow of the heat pump. In particular, the predicted input parameter is thus better suited for the control loop that controls the amount of input heat. Thus, a more stable and robust controlling is ensured.

5 Further, in some aspects, controlling the amount of input heat may further comprise providing an amount of process cooling from the heat pump to one or more process cooling consumers and varying an amount of heat provided by the one or more process cooling consumers to the heat pump to control the amount of input heat.

10 It is to be appreciated that the method comprises providing process cooling by the heat pump in a combined cooling and heating application. Process cooling may aid in cooling a temperature of another medium. Process cooling may be used, for instance, in a refrigerator (as a process cooling consumer). Thereby, the method promotes provision of process heat and process cooling at substantially the same time.

15 It is also to be understood that the amount of heat provided by the one or more process cooling consumers can be varied, which facilitates that the amount of input heat is controlled substantially simultaneously. Thus, a variation of the process cooling may be linked to controlling a heat flow of the heat pump.

20 The present disclosure also relates to a controller for controlling a heat flow of a heat pump wherein the controller is configured to carry out the steps of the methods disclosed herein.

25 The present disclosure also relates to a computer program comprising instructions which, when executed by a controller, cause the controller to perform the steps of the methods disclosed herein.

30 The present disclosure also relates to a heating system, such as a heating system for a food processing system and/or a district heating system, comprising: a controller as described herein, a heat pump, a sensor for measuring the output parameter associated with the amount of process heat provided by the heat pump to a consumer, and an actuator for adjusting an amount of input heat provided to the heat pump.

As an example, the method could be employed in a drying plant. In another example, the drying plant comprises a spray drying apparatus. The list of products which may be spray dried is extensive and include among other ingredients for dairy, food, chemical, agro-chemical, energy, biotechnology, pharmaceutical, healthcare, food additives, food
5 ingredients, microorganisms, proteins, peptides, whey, and many more, and are not limited in application to the examples given but are wide open for all such products. Suitable products may be defined by their drying characteristics and not by their use or origin.

10 The process heat provided by a heat pump as disclosed herein may also be used in a district heating system, which may also be referred to as heat networks or teleheating. This may be a system for distributing heat generated in a centralized location through a system of, e.g., insulated pipes for residential and/or commercial heating requirements. This may include space heating and/or water heating.

15 As an example, the amount of process heat that is provided by the heat pump is provided to a heat exchanger of a consumer of the heating system. Alternatively, the process heat that is provided by the heat pump may be used directly from the process medium of the heat pump.

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Process medium of the heat pump

For example, the process medium of the heat pump may be CO₂ (this may be advantageous for a transcritical process). The process medium may also be referred to
25 as a refrigerant of the heat pump. In one example, controlling the amount of input heat is based on a setpoint of the process medium. This may be understood in such a way that a setpoint, such as a temperature associated with a pressure measurement of the process medium (e.g. a suction pressure) may be applied and used for a prediction of an input parameter associated with the amount of input heat provided to the heat
30 pump.

The process medium may be employed in a transcritical cycle in the heat pump. In such a transcritical cycle, the medium may be found in supercritical phase when heat is provided by the heat pump (i.e. the refrigerant cools down, it may not necessarily

condense). For instance, CO₂ may be found in two-phase (subcritical) phase when heat is absorbed from one or multiple supplies, e.g., from cold water. In the latter case, input heat is provided to the heat pump.

5 CO₂ may be advantageous as it is a natural refrigerant having a relatively low environmental impact. CO₂ may be non-toxic, non-explosive and non-flammable. Another advantage is that heat can be easily released from a broad temperature range, which may render CO₂ particularly useful for heating purposes that serve to heat streams requiring relatively large temperature lifts. Such large temperature lifts may
10 prevail for instance in a spray dryer and/or spray drying process.

In one example, using CO₂ as a refrigerant for a heat pump may provide useful process heat of a consumer at a temperature of at least about 135°C. Furthermore, useful process cooling may be provided for a process cooling consumer at a temperature of at
15 most about 3°C. This may be achieved using a single compression step at a relatively high efficiency.

The refrigerant is not limited to CO₂ and may comprise other refrigerants. It may also be possible that refrigerants, operating in other types of cycles, such as reversed
20 Brayton, subcritical, transcritical, cascade, absorption and/or hybrid absorption/compression cycles, may be included.

It is noted that the method steps as described herein may include all aspects and/or embodiments described herein, even if not expressly described as method steps but
25 rather with reference to an apparatus (or device or system or controller). It is also to be understood that the features and advantages described with reference to an apparatus (or device or system or controller) may equally be applicable to the method steps and vice versa. Moreover, the apparatus (or device or system or controller) as outlined herein may include means for implementing all aspects and/or embodiments as
30 outlined herein, even if these may rather be described in the context of method steps. Furthermore, the features and advantages described with reference to the method steps may equally be applicable to the apparatus (or device or system or controller).

Whether described as method steps, computer program and/or means (e.g. a controller), the functions described herein may be implemented in hardware, software, firmware, and/or combinations thereof. If implemented in software/firmware, the functions may be stored on or transmitted as one or more instructions or code on a computer-readable medium. Computer-readable media include both computer storage media and communication media including any medium that facilitates transfer of a computer program from one place to another. A storage medium may be any available media that can be accessed by a general purpose or special purpose computer. By way of example, and not limitation, such computer-readable storage media can comprise RAM, ROM, EEPROM, FPGA, CD/DVD or other optical disk storage, magnetic disk storage or other magnetic storage devices, or any other medium that can be used to carry or store desired program code means in the form of instructions or data structures and that can be accessed by a general-purpose or special-purpose computer, or a general-purpose or special-purpose processor. The controller as described herein may also be implemented in hardware, software, firmware, and/or combinations thereof, for example, by means of one or more general-purpose or special-purpose computers, and/or a general-purpose or special-purpose processors.

4. Brief description of the figures

In the following, preferred aspects are described, by way of example only. Reference is made to the following accompanying figures:

- Fig. 1 illustrates a block diagram of a cascade control system comprising a master controller and a slave controller according to an aspect of the present disclosure;
- Fig. 2 illustrates a more detailed block diagram of a controller module of a cascade control system comprising a master controller and a slave controller, according to an aspect of the present disclosure;
- Fig. 3 illustrates a schematic view of a heating system employing a method according to an aspect of the present disclosure;
- Fig. 4 illustrates two different operation modes of a cascade control system for a heat pump according to an aspect of the present disclosure;

- Fig. 4a illustrates one of the operation modes of Fig. 4 having improved performance;
- Fig. 5 illustrates a further diagram relating to the aspect of Fig. 4;
- Fig. 6 illustrates a schematic flow chart of a method according to an aspect of the present disclosure;
- Fig. 7 illustrates a schematic view of a heat pump to be controlled by a method according to an aspect of the present disclosure;
- Fig. 8 illustrates a spray dryer as a heating according to an aspect of the present disclosure; and
- Fig. 9 illustrates the spray dryer of Fig. 8 with a heat pump according to an aspect of the present disclosure.

5. Detailed description of the figures

Subsequently, several exemplary aspects of the present disclosure will be outlined, primarily with reference to the above figures. It is noted that further examples are certainly possible, and the below explanations are provided by way of example only, without limitation. Further, the present disclosure can also be used in other aspects not explicitly disclosed hereafter. Moreover, as detailed below, the described aspects are compatible with each other, and individual features of one example may also be applied to another example.

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While specific feature combinations are described in the following with respect to the exemplary aspects of the present disclosure, it is to be understood that not all features of the discussed aspects have to be present for realizing the disclosure, which is defined by the subject matter of the claims. The disclosed aspects may be modified by combining certain features of one exemplary aspect with one or more features of another exemplary aspect. Specifically, the skilled person will understand that features, components and/or functional elements of one exemplary aspect can be combined with technically compatible features, components and/or functional elements of any other example of the present disclosure given that the resulting combination falls within the

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definition of the disclosure provided by the claims. The skilled person also understands that certain features may be omitted in so far as they appear dispensable.

Throughout the present figures and specification, the same reference numerals refer to the same elements. The figures may not be to scale, and the relative size, proportions, and depiction of elements in the figures may be exaggerated for clarity, illustration, and convenience.

Fig. 1 shows a block diagram of a cascade control system 60 comprising a master controller 65 and a slave controller 70 according to an aspect of the present disclosure.

The control system 60 is adapted to control an amount of input heat 10 provided to a heat pump. Such controlling could be done using an actuator, e.g., a valve e.g., configured to adjust a mixing ratio of input fluids of different temperature.

In some configurations, the master controller 65 may receive a temperature measurement of an output fluid (referred to herein as the measured output parameter 26 associated with the amount of process heat) of the heat pump e.g., as a sense-in signal. The master controller 65 may compare it to a temperature setpoint 26,SP for the output fluid (also referred to herein as a setpoint for the output parameter associated with the amount of process heat) of the heat pump. Based on the comparison, the master controller 65 may generate an output signal 66 that may be directly input into the slave controller 70 that may be configured to control the temperature of a fluid providing input heat to the cold side of the heat pump. For example, the output signal 66 of the master controller 65 may be used as a dynamical / floating setpoint for the slave controller 70 to which a measured temperature of the heat input fluid (referred to herein as the measured input parameter 11 associated with the amount of input heat) is compared to.

For instance, if the heat consumers that receive process heat from the heat pump require more heat, the temperature of the output fluid may decrease. The decreased temperature can be measured and sensed by the master controller 65 which, in turn, increases the setpoint used by the slave controller 70. This will then result – in closed loop operation – in an increased temperature of the fluid providing the input heat to

the heat pump. In this manner the illustrated example aspect improves the operation of the heat pump since an increased heating demand results in an increased heat supply. Thereby, the temperature and/or amount of process heat provided by the heat pump and the temperature and/or amount of input heat provided to the heat pump can be controlled at substantially the same time. For instance, a requested heating demand by hot consumers may be provided, while providing simultaneous cooling at temperatures that can be used by cold consumers. This can be performed in a stable manner. In addition, the internal operational parameter(s) of the heat pump, e.g., the compressor's power, may be maintained closer to their efficiency maximum.

In other configurations, the output signal 66 of the master controller 65 may be modified via a pseudo prediction model (PPM), which may be part of the prediction module 80 such as the model according to equation (EQ1) as described herein. In such a configuration, the output 66 of the master controller 65 is not directly input to the slave controller 70, e.g., as a dynamical setpoint but it is modified first based on additional information on the heat pump, its suppliers and / or its consumers, as discussed in detail elsewhere herein and in particular with reference to Fig. 2. The modified setpoint of the slave control is indicated as 66'. For example the temperature setpoint of the slave controller 70 may correspond to a predicted input temperature that is based on an energy balance to ensure stable operation of the heat pump in a large range of output characteristics (e.g. when the output temperature or amount of heat required changes). Also in such a configuration, the operation of the heat pump itself is not affected.

Fig. 2 shows a more detailed block diagram of a prediction module 80 that may be used in a cascade control system 60 as disclosed herein. Various inputs to the prediction module 80 are shown on the left-hand side. The inputs comprise the output of the master controller 65, control signals 67, adjustable prediction model parameters α , η , $+/- \beta$, γ and, additional information / system data 68 on the heating and cooling system in which the heat pump and the heat pump control system is operated in – such as measurements and/or setpoints obtained from the consumers as described elsewhere herein. The control signals 67 can switch between directly feeding the output of the master controller 65 – with or without an additional boost offset (α) – to the slave

controller 70 or using the PPM to obtain a modified, predicted setpoint for the slave controller 70, that can be boosted (using α) or not.

5 In some aspects, the output of the master controller 65 may be used as input for the PPM / prediction module 80. Alternatively or additionally, the inputs of the master controller 65, i.e., the measured output parameter 26 and/or the setpoint of the output parameter 26,SP may be used.

10 Thus, it is to be noted that the input data to the prediction module 80 from the master controller 65 may also comprise the measured output parameter 26 and/or the setpoint of the output parameter 26,SP. The measured output parameter 26 and/or the setpoint of the output parameter 26,SP may also be provided to the prediction module 80 as part of the additional information / system data 68.

15 Importantly, the additional information / system data 68 (for examples see description in section 3. above) allows the prediction module 80 and thereby the PPM to take into account – in a predictive manner – whether the output heat required by the consumers and/or the input heat provided by the suppliers of the heat pump change and by how much. In this manner, the dynamical setpoint that is input to the slave controller 70
20 and thereby the amount of heat supplied to the heat pump can be adjusted to match the predicted system requirements. Thereby, fluctuations, such as control loop oscillations or other instabilities can be avoided. This makes the heat pump particularly useful in applications requiring specific temperatures. The heat pump may also be operable closer to its efficiency maximum.

25 Fig. 3 illustrates a schematic view of a heating system 50 employing a method according to an aspect of the present disclosure. The heating system 50 comprises a controller 60 as described herein. The heating system 50 comprises a heat pump 1. The heating system 50 further comprises a sensor 25 for measuring an output parameter 26
30 associated with an amount of process heat 20. The heating system 50 also comprises an actuator 15 for adjusting an amount of input heat 10 provided to the heat pump 1. For instance, the temperature of the cold-water flow may be varied, such that the process medium of the heat pump 1 absorbs a different amount of heat 10. The actuator 15 is a valve in this example. In particular, the actuator could be a 3-way valve.

The exhaust heat exchanger 40 may be connected to an exhaust air stream of a consumer 30, 30' comprising residual heat that can be harvested by the exhaust heat exchanger 40. Thereby, heat may be transferred from the exhaust air stream to the cold water, which, in turn, may affect the return temperature 11 of the input fluid to the heat pump by the actuator 15.

Exemplarily, an amount of process heat 20 is indicated in this figure by the two connection lines 26, 28 between the heat pump 1 and the consumer 30. In one of the two connection lines (e.g. the connection line corresponding to the measured output parameter 26) a fluid, which may be the hot supply water, is guided from the heat pump 1 to the consumer 30 (supply). In the remaining (return) connection line 28 of the two connection lines 26, 28, said fluid, which may then be less hot return water, is guided from the consumer 30 to the heat pump 1. The amount of process heat 20 may be determined by a temperature 26, mass flow and heat capacity of said fluid. Preferably, also the return temperature 28 is used for determining the amount of process heat 20.

An amount of input heat 10 is indicated in this figure by the two connection lines 11, 12 between the heat pump 1 and the exhaust heat exchanger 40 and/or other supplies 41. In one of the two connection lines (e.g. the connection line corresponding to the measured input parameter 11) a fluid, which may a process medium such as water, is guided from the exhaust heat exchanger 40 and/or the other supplies 41 towards the heat pump 1 (return, as seen from the heat exchanger 40 and/or the other supplies 41). In the remaining (supply) connection line 12 (e.g. the connection line corresponding to the cold supply parameter 12) of the two connection lines 11, 12, said fluid is guided from the heat pump 1 towards the exhaust heat exchanger 40 and/or the other supplies 41. The amount of input heat 10 may be determined by a temperature 11, mass flow and heat capacity of said fluid. Preferably, also the supply temperature 12 is used for determining the amount of input heat 10.

As indicated in this figure, the heating system 50 optionally comprises a further consumer 30'. This further consumer 30' may also receive an amount of process heat 20 provided by the heat pump 1. The heat pump 1 may operate using a process

medium, preferably CO₂, as a refrigerant. In one example, controlling the amount of input heat may be based on a temperature setpoint of the medium as described herein and in particular with reference to the energy balance below.

5 Energy balance

An aspect of the method of the present disclosure will now be illustrated by way of an energy balance (which may be part of the pseudo prediction model, PPM, which is part of the prediction module 80 referred to herein) and with reference to Fig. 3.

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The method may comprise determining, based on obtained additional information, an energy balance of the heat pump. The energy balance of the heat pump may be formulated as follows:

15

$$Q_{Heating} = Q_{Cooling} + W_{Compressor} + Q_{Loss}$$

$Q_{Heating}$ is the heat energy e.g. measured in Joule leaving the heat pump per unit of time, such that $[Q_{Heating}] = \text{J/s}$. It may be assumed that losses are negligible and/or very small ($Q_{Loss} \sim \text{zero}$). $Q_{Heating}$ may be the process heat provided by the heat pump to one or more consumers, $Q_{Cooling}$ may be the input heat provided to the heat pump (e.g. heat provided by a process medium, such as a process medium returned from the exhaust heat exchanger 40 and/or the other suppliers 41). $W_{Compressor}$ is the (electrical) power of the one or more compressors of the heat pump (e.g., the power needed for compressing the process medium of the heat pump), such that $[W_{Compressor}] = \text{J/s}$.

25

The term $Q_{Heating}$ may equal the sum of the process heat provided to each consumer (e.g. if multiple consumers are applied), as follows.

$$Q_{Heating} = Q_{Main} + Q_{rest}$$

30

The term Q_{Main} may be the heat provided (per unit of time) to a first consumer 30, such as the main heater, that requires the majority of the heat output of the heat pump. The term Q_{rest} may be the heat provided to one or more second consumers 30'.

The term $Q_{Cooling}$ may be expressed as

$$Q_{Cooling} = m_{cold} \cdot c_p (T_{rtn,cold} - T_{sup,cold})$$

5 Herein, m_{cold} is the mass flow rate (e.g. of the cooling medium water) and c_p is the (isobaric) heat capacity of said medium. $T_{rtn,cold}$ is a return temperature (e.g. the temperature of the cooling medium flowing from one or more cooling consumers / heat suppliers 41 back towards the heat pump 1) and $T_{sup,cold}$ 12 is a supply temperature (e.g. the temperature of the cooling medium leaving the heat pump 1 towards one or
10 more cooling consumers / heat suppliers 41). The mass flow leaving the heat pump 1 may be directed to process cooling consumers 41, which could advantageously use this mass flow as process cooling.

In said aspect, the method comprises predicting, based on the determined energy
15 balance, an input parameter associated with the amount of input heat 10 provided to the heat pump 1.

The parameter associated with the amount of input heat 10 is a temperature of an input fluid. The input fluid could be the process medium of the exhaust heat exchanger 40
20 and/or the other supplies 41 (cooling consumers).

The temperature of the input fluid may be the return temperature $T_{rtn,cold}$. The energy balance discussed above may thus be used to obtain the following equation (EQ1) which allows to predict the cooling medium return temperature $T_{rtn,cold}$ of the input fluid that
25 provides the input heat to the heat pump:

$$T_{rtn,cold} = T_{sup,cold}^* + \frac{Q_{Main} + Q_{rest}^* - W_{Compressor}}{m_{cold} \cdot c_{p,water}} + \alpha$$

In this equation, the asterisk of $T_{sup,cold}^*$ means that $T_{sup,cold}$ (i.e. the temperature of
30 the cooling medium leaving the heat pump to the cooling consumers 41) is not measured directly but instead, $T_{sup,cold}^*$ is predicted from a setpoint for the saturated temperature (STaSP) at suction pressure of the heat pump process medium / refrigerant (assuming stable operation) via:

$$T_{sup,cold}^* = STaSP,SP + \eta$$

The setpoint $STaSP,SP$ may be used to control a capacity of one or more compressors of the heat pump. The saturated temperature ($STaSP$) at suction pressure may be the temperature at which a substance of specific pressure may change its state from liquid to vapor. The term η may be a model parameter, which models a difference between the setpoint $STaSP,SP$ and $T_{sup,cold}^*$ at typical (e.g., stable) operation conditions of the heat pump. It was found that this improves stability of the method for controlling a heat flow of the heat pump 1. Such an improvement may not be achieved using directly measured values for the cold-water supply temperature 12, which would be denoted herein as $T_{sup,cold}$, i.e. without asterisk.

The term α in above equation may be a further model parameter used for start-up processes (or modes), as described above. For example, α may be applied to increase the prediction value of the return temperature $T_{rtn,cold}$. Thereby, the input heat provided to the heat pump 1 is increased since the dynamic / floating setpoint of the slave controller is increased by an amount α . In case the heat pump 1 is not in a start-up mode, the term is set to zero, i.e., disabled.

20

The remaining terms in EQ1, Q_{Main}^* and Q_{rest}^* , may be defined as follows

$$Q_{Main}^* = m_{Main} \cdot c_{p,air} (T_{Main,air,out,SP} - T_{Main,air,in})$$

$$Q_{rest}^* = m_{rest} \cdot c_{p,air} (T_{air,out,SP} - T_{air,in})$$

25

Here, again, the asterisk indicates that Q_{Main}^* and Q_{rest}^* are not directly determined from measured quantities only but predicted from a temperature setpoint of the corresponding consumer (denoted as T with index "SP"). The temperature setpoints represent target values for the corresponding consumers, such as target temperatures of air streams providing heat to a dryer (see Fig. 8) or a similar heat consumer. For prediction it is assumed that the consumers operate close to or in stable conditions and that thus the setpoint indicates the actual value.

30

Equation (EQ1) makes advantageously use of parameters that are predicted for next stable states and actual (measured) variables while controlling the system to reach a stable state. Thus, the equation may also be termed a pseudo prediction model (PPM).

- 5 It is to be noted that in the above equations for determining Q_{Main}^* the temperature setpoint $T_{Main,air,out,SP}$ can be linked to the setpoint for the output parameter 26,SP ($T_{sup,hot,SP}$) of the heat pump as follows:

$$T_{Main,air,out,SP} = T_{sup,hot,SP} - \gamma^*$$

10

- The above equation comprises the term γ^* , which represents a temperature offset between the setpoint for the hot supply temperature of the heat pump and the temperature setpoint of a consumer (the main air in this example). Thus, the setpoint of the consumer is lower compared to the setpoint for the hot supply temperature (the offset being a positive value). In some aspects, the actual value of the hot supply temperature $T_{sup,hot}$ can be used in the above equation instead of its setpoint. Further, in some aspects, the term γ^* may be understood as the term γ .

- 20 As an example, the offset can be about 10°C, 20°C, 24°C or 30°C. The value of the offset may depend on components used within and/or in proximity to the heat pump, e.g. heat exchanger, piping, efficiencies of components and the like. Accordingly, the (measured/actual value of the /setpoint of the) output parameter 26 is used for controlling an amount of input heat provided to the heat pump 1.

- 25 A particular contribution of this disclosure is that equation EQ1 facilitates to determine a dynamic / floating setpoint for the return temperature of the cooling fluid, $T_{rtn,cold}$, which reduces fluctuations as described herein.

- 30 It is to be noted that the difference between the outlet main heater and the inlet main heater temperature, $T_{Main,air,out} - T_{Main,air,in}$, may be derived from the heater as shown between the “cold air” and “hot air” in Fig. 8 in the upper left part. Therein a heat may be exchanged from the hot supply water (not shown) and the main air and, accordingly, the main air temperature leaving the heater (Fig. 8) is referred to as the outlet air ($T_{Main,air,out}$), which is then entering the dryer of Fig. 8.

Fig. 4 illustrates (in three diagrams) two different operation modes of a cascade control system 60 for a heat pump 1 according to an aspect of the present disclosure. The master controller may be configured as described herein (i.e. receiving a temperature measurement of an output fluid and comparing it to a temperature setpoint thereof).

A parameter associated with an amount of input heat provided to the heat pump, e.g. the return temperature $T_{rtn,cold}$, is used as a setpoint for a slave controller in the cascade control as described herein. In particular, the return temperature $T_{rtn,cold}$ is predicted from the energy balance according to equation (EQ1) as described herein, which is applied as the PPM between the master and the slave controller in the cascade control. Thereby, the setpoint of the slave controller is dynamically adjusted. This allows to direct the slave setpoint temperature, i.e. a setpoint of the temperature $T_{rtn,cold}$ to the predicted value based on equation (EQ1).

The so established linkage between the predicted temperature $T_{rtn,cold}$ (inter alia using measured output parameters associated with the amount of process heat provided by the heat pump), and the slave controller was found to be beneficial to provide an improved control of a heat flow of a heat pump.

The predicted value $T_{rtn,cold}$ of the above equation (EQ1) can be limited within a range (e.g. $\pm \beta$) about the actual measurement value. This limitation can account for (large) differences between the prediction and actual temperatures, so that the prediction does not deviate too much from the actual temperatures. Thereby, the limitation accommodates for, e.g., heat losses and/or non-constant parameters. For instance, the value of β could be about 1°C. The model parameter alpha α of equation (EQ1) could be 5°C. The model parameter eta η of equation (EQ1) could be 1.5°C.

In the diagrams of Fig. 4, the setpoint of the hot supply temperature $T_{sup,hot,SP}$, is changed by 5 K from 131°C to 126°C (first example) and from 130°C to 125°C (second example).

Two examples of the method described herein are shown: a first example, plotted in solid lines and a second example, plotted in dashed lines.

The top diagram of Fig. 4 shows the response of the master controller, i.e. the hot supply temperature $T_{sup,hot}$ (26), which is a temperature associated with an amount of process heat provided by the heat pump. Furthermore, the temperature setpoint $T_{sup,hot,SP}$ (26,SP) is shown. The middle diagram shows the response of the slave control, i.e. the temperature $T_{rtn,cold}$ (11). The bottom diagram shows the response of the valve control, i.e. the valve opening of actuator 15 (Fig. 2) in %. The valve opening adjusts a mixing ratio of several fluids of different temperature.

In the first example of the PPM (solid lines), actual measurements for the cold supply temperature $T_{sup,cold}$ (the temperature leaving the heat pump) are employed in equation (EQ1) instead of the modified term $T_{sup,cold}^*$. The results show that the temperature 26 does not stabilize but fluctuates (i.e. it does not quickly align to its setpoint 26,SP). Also the predicted cold return temperature 11 fluctuates (Fig. 5, termed “PPM”). Accordingly, the setpoint of the slave control fluctuates 11,SP (Fig. 4, middle diagram), which causes also the master output 26 to fluctuate (Fig. 4, top diagram). In Fig. 5, an upper bound of 15°C is provided, to prevent the saturated temperature at suction pressure STaSP of the refrigerant reaching 15°C. This may activate a controller safety function of the heat pump, causing a reduction of the compressor capacity.

In the second example of the PPM (dashed lines), the term $T_{sup,cold}^*$ rather than $T_{sup,cold}$ is employed in equation (EQ1) as described herein. The results show improved stabilizing and a robust curvature of the temperature $T_{sup,hot}$ (26, example 2) (Fig. 4, top diagram). In particular, the results show that the temperature 26 (example 2) quickly aligns with its setpoint 26,SP. Also the predicted cold return temperature $T_{rtn,cold}$ (11, example 2) does not substantially fluctuate (Fig. 4, middle diagram, dashed lines). The second example of the PPM is shown in greater detail in Fig. 4a.

Without wishing to be bound by any theory, the inventors are of the opinion that the difference between the first example and the second example may be explained according to the following.

Starting from the equation (EQ1) above and assuming the term α to be zero (for normal operation, i.e. no start-up mode or the like), the terms on the right-hand side of

equation (EQ1) may be reformulated to yield four temperatures ($T_{sup,cold}^*$, T_{Main} , T_{rest} and T_{Compr}) as follows.

$$T_{rtn,cold} = T_{sup,cold}^* + T_{Main} + T_{rest} + T_{Compr}$$

5

Tests indicate that from the four above temperatures, the temperature $T_{sup,cold}^*$ has the largest contribution (based on absolute values) in predicting the cold return temperature $T_{rtn,cold}$. Thus, a fluctuation of this temperature may adversely affect a stable operation. Further tests indicate that, employing the first example of the PPM, i.e. using actual measurements for the cold supply temperature $T_{sup,cold}$, can lead to fluctuations of the temperature $T_{sup,cold}$, which consequently affects stability of the predicted temperature $T_{rtn,cold}$. In turn, the setpoint for the slave controller fluctuates.

When employing the second example of the PPM, i.e. using the modified value $T_{sup,cold}^*$ said temperature is substantially stable. Using a setpoint for the saturated temperature at suction pressure STaSP,SP (as described herein, this could be derived based on a pressure measurement of the suction pressure) of 5°C and a value of eta η of 1.5°C, the value of $T_{sup,cold}^*$ would be substantially stable at about 6.5°C.

Fig. 6 illustrates a schematic flow chart of a method 100 according to an aspect of the disclosure. Optional method steps may be indicated in this figure by a dashed box.

The method 100 comprising measuring 110 an output parameter 26 associated with an amount of process heat provided by the heat pump to a consumer; controlling 120, based on the measured output parameter 26, an amount of input heat provided to the heat pump.

This method beneficially provides for an improved and stable operation of the heat pump. As an example, it is appreciated that no buffer tank may be required for heating purposes. Thus, the method provides cost-effective controlling of the heat pump.

Optionally, controlling 120 the amount of input heat provided to the heat pump comprises controlling 130 a temperature and/or a flow rate of an input fluid providing the input heat to the heat pump.

Optionally, controlling 120 the amount of input heat comprises adjusting 140, preferably dynamically, a transfer function and/or a setpoint of a control loop controlling the amount of input heat.

5

Optionally, the method 100 further comprises obtaining 150 one or more of the following additional information: a temperature setpoint associated with the amount of process heat, a temperature setpoint associated with the amount of input heat, a thermal and optionally measured parameter associated with the amount of process
10 heat, a thermal and optionally measured parameter associated with the amount of input heat, a setpoint of the heat pump, optionally a temperature setpoint of a process medium of the heat pump, an operational and optionally measured parameter of the heat pump, preferably the measured electrical power consumption of the heat pump; and controlling 135, based on the obtained additional information, the amount of input
15 heat provided to the heat pump.

Optionally, controlling 120 the amount of input heat based on the obtained additional information comprises: determining 160, based on the obtained additional information, an energy balance of the heat pump; predicting 170, based on the
20 determined energy balance, an input parameter associated with the amount of input heat provided to the heat pump.

Optionally, the method 100 further comprises: adjusting 145 the transfer function and/or the setpoint of the control loop controlling the amount of input heat based on
25 the predicted input parameter.

Optionally, controlling 120 the amount of input heat further comprises: providing 180 an amount of process cooling from the heat pump to one or more process cooling consumers; and varying 190 an amount of heat provided by the one or more process
30 cooling consumers to the heat pump to control the amount of input heat.

With reference to Fig. 1 it is noted that the depicted controller 60 is a controller 60 for controlling a heat flow of a heat pump wherein the controller 60 is configured to carry out the method 100 according to the aspect of Fig. 6. In particular, the controller 60

comprises means for storing instructions, which when executed cause the controller to carry out the method of Fig. 6.

Fig. 7 shows a schematic view of a heat pump 1 to be controlled by a method according to an aspect of the present disclosure. The figure shows the cycle of the process medium of the heat pump 1. In this example, CO₂ is used as the process medium (i.e. as the refrigerant). Cold water 5a is provided and feeds a heat exchanger 5 on the cold side of the heat pump 1. Thereby, the refrigerant absorbs heat and evaporates in the evaporator 3. The refrigerant is directed to the optional heat exchanger 6''' (the refrigerant may be heated therein, for instance by a fraction of the water heated in the heat exchanger 6'), then it is compressed in the compressor 2. Downstream the compressor 2, the refrigerant is guided to the heat exchanger 6'', to heat up hot water 8. Subsequently, it is guided to the heat exchanger 6' to heat up warm water 7 and then to another optional heat exchanger 6, in which a remaining heat of the refrigerant can be used to heat up refrigerant downstream the evaporator 3 (e.g. as a recuperator). Downstream the optional heat exchanger 6, the refrigerant is guided through the expansion valve 4. Due to the expansion, the refrigerant may be liquified. Some of the refrigerant may bypass the evaporator 3 as shown in this figure, however, different configurations may also be possible (e.g. without bypassing). It may also be possible that a part of the warm water from 7 is directed to the heat exchanger 6''. This may be an alternative to using the heat exchanger 6.

The compressor 2 may be operating at a power of about 1 kW. About 2 kW of input heat may be provided from cold water 5a to the refrigerant through the heat exchanger 5 on the cold side (i.e. the evaporator 3). Thus, in total, about 3 kW of heat may be provided to the hot water 8 and the warm water 7. As heat is a cost intensive good, such a heat pump 1 may provide a cost-effective provision of heat.

Further, usage of the input heat provided to the refrigerant as process cooling for the cold water 5a may provide an additional benefit. For instance, when a typical heat pump is applied for providing heat to a household, heat is provided from ambient air. Thus, cooling is done by the outside air, which does not add an additional benefit. However, integrating the cooling as useful process cooling could pave the way to provide an additional benefit and to add value.

Fig. 8 shows a heating system according to an aspect of the present disclosure. The heating system 50 of this example is a spray dryer, which may be used for food processing. A spray dryer (or the spray drying process) is applied to convert liquid and/or slurry feeds into dry powders using a hot medium, such as a hot gas. A spray dryer requires high drying temperatures to drive the evaporation of solvents and to generate powders. The solid contents could be above 95%. The drying air conditions should be kept stable for relatively long periods, such as days or weeks. Air heating is modulated to reach the required drying temperatures. The high temperatures of the air heating (and optional dehumidification) make spray drying highly energy intensive. For instance, dairy spray dryers may conventionally require about 1.2 kWh heating per kg powder produced with drying air temperatures in the range of about 200°C to 240°C.

The heating system 50 comprises: a controller 60 as described herein; a heat pump 1; a sensor for measuring an output parameter associated with an amount of process heat; and an actuator 15 for adjusting an amount of input heat provided to the heat pump. The controller 60, the heat pump 1 and the actuator 15 are indicated as boxes.

Multiple consumers are shown in this figure, such as the drying chamber 30, the static fluid bed 30', the vibro fluidizer 30'', the bag filter 30''' and the nozzle 30'''. A vibro fluidizer may be understood as a type of fluidized bed where the mechanical vibration enhances the performance of fluidization process. As an example, the vibro fluidizer may be a vibrating fluid bed of the plug flow type, where a powder layer is vibrated on an air distributor plate. All consumers require at least a part of process heat. The consumers may also be referred to as subsystems, receiving at least part of the process heat.

The term $Q_{Heating}$ of the above equation (EQ1) is thus extended to include the heat of further consumers (i.e., Q_{rest} of EQ1 is further extended as detailed below):

30

$$Q_{Heating} = Q_{Main} + Q_{SFB} + Q_{Nozzle} + Q_{Bagfilter} + Q_{VF} + Q_{Reg}$$

Q_{Main} is the heat of a main heater, Q_{SFB} is the heat of the static fluid bed, Q_{Nozzle} is the heat of the nozzle, $Q_{Bagfilter}$ is the heat of the bag filter, Q_{VF} is the heat of the vibro fluidizer, Q_{Reg} is the heat of the regeneration (not explicitly shown in this figure).

- 5 Further, the energy balance can be used to obtain the following equation (EQ1e) which allows to predict the return temperature $T_{rtn,cold}$ of the input fluid that provides the input heat to the heat pump.

$$T_{rtn,cold} = T_{sup,cold}^* + \frac{Q_{Main}^* + Q_{SFB}^* + Q_{Nozzle}^* + Q_{Bagfilter}^* + Q_{VF}^* + Q_{Reg}^* - W_{Compr}}{m_{cold} \cdot c_{p,water}} + \alpha$$

10

The terms in the equation (EQ1e) are defined as described above with respect to equation (EQ1).

- 15 Fig. 9 shows the spray dryer as a heating system 50 of Fig. 8 with a heat pump 1 according to an aspect of the present disclosure. An amount of input heat 10 provided to the heat pump 1 and an amount of process heat 20 provided by the heat pump 1 to a consumer is shown. The spray dryer of this figure is a multi-stage dryer (MSD).

- 20 S1 indicates is a step of ice-water (or cold water) dehumidification. Herein cold water is applied to cool incoming air below dewpoint. Thereby, humidity from air is substantially removed, which makes the drying process more efficient.

- 25 In S2, air for the vibro fluidizer is cooled. This is advantageous as the resulting powder of the heating system should not be too warm when it is further processed (e.g. packaged).

S3 indicates process cooling, which can be used to cool other processes. This may be used for cooling lactose for crystallization and/or cooling milk, which may help to keep it fresh.

- 30 In S4, exhaust air is cooled down. This may be performed in an exhaust heat exchanger 40 as shown in Fig. 3. Cooling the exhaust air facilitates that the amount of input heat 10 to the heat pump 1 is provided. E.g., the temperature of the cold-water supply can thereby be influenced, if an opening degree of a valve (as best seen in Fig. 3, reference

sign 15) between the exhaust heat exchanger in S4 (40 in Fig. 3) and the heat pump 1 is varied.

On the hot side of the heat pump 1, a warm water ($\sim 75^{\circ}\text{C}$) and a hot water ($\sim 135^{\circ}\text{C}$) cycle are shown. The hot water temperature may be the temperature referred to as 26 in Figs. 4 and 4a. Attributable to the physical properties of CO_2 , more heat at low temperature (75°C) than at high temperature (135°C) is provided.

In S5, frost protection is performed. This could be useful for instance during winter times to ensure that air is warmer than 0°C to prevent ice in the air ducting.

In S6, heating the air that is used for the regeneration of the desiccant wheel (a desiccant wheel may be understood as a wheel for drying the air). This can dry the air more than the ice-water dehumidification. Hot air may be required to regenerate the wheel: The humidity that the wheel has adsorbed from the main air is removed again as vapor in the regeneration air. A desiccant wheel can dry the air to lower humidity than the ice-water condenser. In this manner, it can be an advantage to use both means of dehumidification. This arrangement also allows to advantageously use the cooling in the ice-water condenser which increases the overall efficiency. In addition, a balance can be made between the used cooling and the used heating.

In S7 and S8 heat exchangers are indicated, some of which may use only the warm water and not the hot water to heat the fluid of the spray dryer. Overall, more heat at low temperature than at high temperature is applied (as more heat at low temperature than at high temperature is available). Preferably, in each of S7 and S8 one heat exchanger using warm water and one heat exchanger using hot water is applied.

In S9, an additional heat exchanger for the main air is shown. This is advantageous, as the main air of the spray dryer should be around 200°C . Usually, the heat for this heat exchanger cannot be delivered by the heat pump 1. This heat exchanger could also be used for starting the spray dryer, when the heat pump 1 is not yet working at full capacity. As an example, the heat pump 1 may not be working at full capacity, if the exhaust air in S4 is not yet warm enough. It may be understood that at least a sufficient amount of input heat is required for the control method described herein (as the

controlled valves of the slave controller adjust a certain mixing to meet a setpoint for the temperature of the input fluid to the heat pump).

5 The control of the heat pump 1 in this example by the controller 60 is performed as described herein. The advantages of such a controlling become particularly apparent considering the following:

10 A spray dryer is typically facing disturbances in operating conditions. One common disturbance is a change of weather. When the ambient humidity changes, the necessary mass flow of ice water to the ice water dehumidifier also changes. If the control method cannot adapt quickly to such sudden changes, the spray dryer operates without adequate dehumidification for a substantial period. This in turn adversely affects the energy required for heating. If the heat pump cannot keep the temperature of hot water stable, more energy for additional heating of the air streams is required for operating
15 the spray dryer.

At start-up of the spray dryer, the spray dryer is heated to an operating temperature. If this operating temperature does not meet the requirements (i.e. if it is too high or too low), this impairs the product's quality and/or the production capacity is reduced.
20 Thus, a fast and accurate controlling of the spray dryer is of importance to facilitate a quick start-up of the plant.

The method described herein is not limited to the above example. A further example, for which the method is particularly useful is Clean-in-Place (CIP) applications. CIP is a
25 method of cleaning the interior surfaces of pipes, vessels, equipment, filters and associated fittings without disassembling the components. CIP benefits from applying hot water at a specified constant temperature, wherein the hot water is merely used once for cleaning the components. Furthermore, the method according to the present disclosure may be used in wash down, batch cooking, blanching and/or scalding
30 applications. All these applications also make use of hot water, which is preferably used once. Further examples include de-humidification and/or driers, which require combined heating and cooling. Preferably, an air stream is cooled to reduce the air humidity and then, heated to provide a hot air stream with a low relative humidity to de-humidify and/or dry products. Another example is the provision of boiler make up

water. Further, the method described herein may be applied in the context of district heating, having a low return temperature.

5 The foregoing disclosure provides illustration and description but is not intended to be exhaustive or to limit the aspects to the precise form disclosed. Modifications and variations may be made in light of the above disclosure or may be acquired from practice of the aspects.

10 It will be apparent that systems and/or methods described herein may be implemented in different forms of hardware, firmware, or a combination of hardware and software. The actual specialized control hardware or software code used to implement these systems and/or methods is not limiting of the aspects. Thus, the operation and behavior of the systems and/or methods were described herein without reference to specific software code—it being understood that software and hardware can be
15 designed to implement the systems and/or methods based on the description herein. Even though particular combinations of features are recited in the claims and/or disclosed in the specification, these combinations are not intended to limit the disclosure of various aspects. In fact, many of these features may be combined in ways not specifically recited in the claims and/or disclosed in the specification. Although
20 each dependent claim listed below may directly depend on only one claim, the disclosure of various aspects includes each dependent claim in combination with every other claim in the claim set. A phrase referring to “at least one of” a list of items refers to any combination of those items, including single members. As an example, “at least one of: a, b, or c” is intended to cover a, b, c, a-b, a-c, b-c, and a-b-c, as well as any
25 combination with multiples of the same element (e.g., a-a, a-a-a, a-a-b, a-a-c, a-b-b, a-c-c, b-b, b-b-b, b-b-c, c-c, and c-c-c or any other ordering of a, b, and c).

30 No element, act, or instruction used herein should be construed as critical or essential unless explicitly described as such. Also, as used herein, the articles “a” and “an” are intended to include one or more items and may be used interchangeably with “one or more.” Furthermore, as used herein, the terms “set” and “group” are intended to include one or more items (e.g., related items, unrelated items, a combination of related and unrelated items, and/or the like), and may be used interchangeably with “one or more.” Where only one item is intended, the phrase “only one” or similar

language is used. Also, as used herein, the terms “has,” “have,” “having,” and/or the like are intended to be open-ended terms. As used herein, the term “component” is intended to be broadly construed as hardware, firmware, or a combination of hardware and software. As used herein, a processor is implemented in hardware, firmware, or a combination of hardware and software.

As used herein, the phrase “based on” shall not be construed as a reference to a closed set of information, one or more conditions, one or more factors, or the like. In other words, the phrase “based on A” (where “A” may be information, a condition, a factor, or the like) shall be construed as “based at least on A” unless specifically recited differently.

As used herein, the term “or” is an inclusive “or” unless limiting language is used relative to the alternatives listed. For example, reference to “X being based on A or B” shall be construed as including within its scope X being based on A, X being based on B, and X being based on A and B. In this regard, reference to “X being based on A or B” refers to “at least one of A or B” or “one or more of A or B” due to “or” being inclusive. Similarly, reference to “X being based on A, B, or C” shall be construed as including within its scope X being based on A, X being based on B, X being based on C, X being based on A and B, X being based on A and C, X being based on B and C, and X being based on A, B, and C. In this regard, reference to “X being based on A, B, or C” refers to “at least one of A, B, or C” or “one or more of A, B, or C” due to “or” being inclusive. As an example of limiting language, reference to “X being based on only one of A or B” shall be construed as including within its scope X being based on A as well as X being based on B, but not X being based on A and B.

When reference is made herein to a “component”, “unit”, “device” or the like, this should not be understood as limiting to a particular “component”, “unit”, “device” or the like, but should encompass equivalents that could have similar and/or the same functions.

The term “fluctuations” of a parameter/value or the like may be understood as any (significant) variations of said parameter/value or the like with respect to a more or less constant value and/or a targeted value. The “fluctuations” may also be understood as

variations occurring over a time period. A reduction of “fluctuations” of a parameter/value or the like may be understood as a decrease of said variations of a parameter/value or the like.

6. List of reference signs

5	1	heat pump
	2	compressor
	3	evaporator
	4	expansion valve
	5a	cold water
10	5	heat exchanger (on cold side of a heat pump)
	6, 6', 6'', 6'''	heat exchanger(s) (on hot side of a heat pump)
	7	warm water
	8	hot water
	9	cold water
15	10	amount of input heat
	11	measured input parameter (return temperature)
	12	(cold) supply temperature
	15	actuator
	20	amount of process heat
20	25	sensor, e.g. a temperature sensor
	26	measured output parameter (supply temperature)
	26,SP	setpoint of measured output parameter (supply temperature)
	28	hot return temperature
	30, 30', 30''	consumer(s)
25	30''', 30''''	consumer(s)
	40	exhaust heat exchanger
	41	supplies, process cooling consumers
30	PPM	pseudo prediction model
	SP	setpoint
	SSP	saturated suction pressure

	STaSP	saturated temperature (temperature at saturated conditions) at suction pressure
	STaSP,SP	setpoint for saturated temperature (temperature at saturated conditions) at suction pressure
5		
	50	heating system
	60	controller / control system
	65	master controller
	66	output (signal) of the master controller
10	66'	modified setpoint for the slave controller
	67	control signals
	68	system data
	70	slave controller
	80	prediction module
15		
	100	method
	110	measuring an output parameter associated with an amount of process heat provided by the heat pump to a consumer
	120	controlling, based on the measured output parameter, an amount of
20		input heat provided to the heat pump
	130	controlling a temperature and/or a flow rate of an input fluid providing the input heat to the heat pump
	135	controlling, based on the obtained additional information, the amount of input heat provided to the heat pump
25	140	adjusting, preferably dynamically, a transfer function and/or a setpoint of a control loop controlling the amount of input heat
	145	adjusting, preferably dynamically, the transfer function and/or the setpoint of the control loop controlling the amount of input heat based on the predicted input parameter
30	150	obtaining additional information
	160	determining, based on the obtained additional information, an energy balance of the heat pump

- 170 predicting, based on the determined energy balance, an input
parameter associated with the amount of input heat provided to the
heat pump
- 180 providing an amount of process cooling from the heat pump to one or
5 more process cooling consumers
- 190 varying an amount of heat provided by the one or more process cooling
consumers to the heat pump to control the amount of input heat

In the following, further embodiments are described to facilitate the understanding of the invention:

1. A method (100) for controlling a heat flow of a heat pump, the method (100)
5 comprising
measuring (110) an output parameter (26) associated with an amount of
process heat provided by the heat pump to a consumer;
controlling (120), based on the measured output parameter (26), an
amount of input heat provided to the heat pump.
10
2. The method (100) according to the preceding embodiment,
wherein controlling (120) the amount of input heat provided to the heat
pump comprises:
controlling (130) a temperature and/or a flow rate of an input fluid
15 providing the input heat to the heat pump.
3. The method (100) according to any one of the preceding embodiments,
wherein the measured output parameter (26) comprises one or more of
the following:
20 an output energy flow,
an output power,
an output mass flow,
an output temperature,
an output volume flow, and
25 an output flow velocity associated with an output fluid of the heat pump.
4. The method (100) according to any one of the preceding embodiments,
wherein controlling (120) the amount of input heat comprises:
adjusting (140), preferably dynamically, a transfer function and/or a
30 setpoint of a control loop controlling the amount of input heat.
5. The method (100) according to any one of the preceding embodiments, further
comprising:
obtaining (150) one or more of the following additional information:

- a temperature setpoint associated with the amount of process heat,
a temperature setpoint associated with the amount of input heat,
a thermal and optionally measured parameter associated with the
amount of process heat,
5 a thermal and optionally measured parameter associated with the
amount of input heat,
a setpoint of the heat pump, optionally a temperature setpoint of a
process medium of the heat pump,
an operational and optionally measured parameter of the heat pump,
10 preferably the measured electrical power consumption of the heat pump; and
controlling (135), based on the obtained additional information, the
amount of input heat provided to the heat pump.
6. The method (100) according to the preceding embodiment,
15 wherein controlling (120) the amount of input heat based on the
obtained additional information comprises:
determining (160), based on the obtained additional information, an
energy balance of the heat pump;
predicting (170), based on the determined energy balance, an input
20 parameter associated with the amount of input heat provided to the heat pump.
7. The method (100) according to embodiment 6, wherein the predicted input
parameter comprises a temperature of an input fluid providing the input heat to
the heat pump.
- 25 8. The method (100) according to embodiment 4 and any one of embodiments 6 or
7, further comprising:
adjusting (145) the transfer function and/or the setpoint of the control
loop controlling the amount of input heat based on the predicted input
30 parameter.
9. The method (100) according to any one of the preceding embodiments, wherein
controlling (120) the amount of input heat further comprises:

providing (180) an amount of process cooling from the heat pump to one or more process cooling consumers; and

varying (190) an amount of heat provided by the one or more process cooling consumers to the heat pump to control the amount of input heat.

5

10. A controller (60) for controlling a heat flow of a heat pump wherein the controller is configured to carry out the method (100) according to any one of the preceding embodiments 1 to 9.

10

11. A computer program comprising instructions which, when executed by a controller, cause the controller to perform the method (100) according to any one of embodiments 1 to 9.

15

12. A heating system (50) for a food processing system or a district heating system, comprising:

15

a controller (60) according to embodiment 10;

a heat pump (1);

a sensor (25) for measuring (110) the output parameter (26) associated with the amount of process heat provided by the heat pump (1) to a consumer

20

(30); and

an actuator (15) for adjusting an amount of input heat provided to the heat pump (1).

Claims

1. A method (100) for controlling a heat flow of a heat pump, the method (100) comprising
5 measuring (110) an output parameter (26) associated with an amount of process heat provided by the heat pump to a consumer;
 controlling (120), based on the measured output parameter (26), an amount of input heat provided to the heat pump, wherein controlling (120) the amount of
10 input heat provided to the heat pump comprises:
 controlling (130) a temperature of an input fluid providing the input heat to the heat pump using a valve configured to adjust a mixing ratio of input fluids of different temperature.
15
2. The method (100) according to claim 1,
 wherein the measured output parameter (26) comprises one or more of the following:
 an output energy flow,
20 an output power,
 an output mass flow,
 an output temperature,
 an output volume flow, and
 an output flow velocity associated with an output fluid of the heat pump.
25
3. The method (100) according to any one of the preceding claims,
 wherein controlling (120) the amount of input heat comprises:
 adjusting (140), preferably dynamically, a transfer function and/or a setpoint of a control loop controlling the amount of input heat.
30
4. The method (100) according to any one of the preceding claims, further comprising:

- obtaining (150) one or more of the following additional information:
a temperature setpoint associated with the amount of process heat,
a temperature setpoint associated with the amount of input heat,
a thermal and optionally measured parameter associated with the
5 amount of process heat,
a thermal and optionally measured parameter associated with the
amount of input heat,
a setpoint of the heat pump, optionally a temperature setpoint of a
process medium of the heat pump,
10 an operational and optionally measured parameter of the heat pump,
preferably the measured electrical power consumption of the heat pump; and
controlling (135), based on the obtained additional information, the
amount of input heat provided to the heat pump.
- 15 5. The method (100) according to the preceding claim,
wherein controlling (120) the amount of input heat based on the
obtained additional information comprises:
determining (160), based on the obtained additional information, an
energy balance of the heat pump;
20 predicting (170), based on the determined energy balance, an input
parameter associated with the amount of input heat provided to the heat pump.
- 25 6. The method (100) according to claim 5, wherein the predicted input parameter
comprises a temperature of an input fluid providing the input heat to the heat
pump.
7. The method (100) according to claim 3 and any one of claims 5 or 6, further
comprising:
adjusting (145) the transfer function and/or the setpoint of the control
30 loop controlling the amount of input heat based on the predicted input
parameter.
8. The method (100) according to any one of the preceding claims, wherein
controlling (120) the amount of input heat further comprises:

providing (180) an amount of process cooling from the heat pump to one or more process cooling consumers; and

varying (190) an amount of heat provided by the one or more process cooling consumers to the heat pump to control the amount of input heat.

5

9. A controller (60) for controlling a heat flow of a heat pump wherein the controller is configured to carry out the method (100) according to any one of the preceding claims 1 to 8.

10

10. A computer program comprising instructions which, when executed by a controller, cause the controller to perform the method (100) according to any one of claims 1 to 8.

15

11. A heating system (50) for a food processing system or a district heating system, comprising:

a controller (60) according to claim 9;

a heat pump (1);

a sensor (25) for measuring (110) the output parameter (26) associated with the amount of process heat provided by the heat pump (1) to a consumer (30); and

20

an actuator (15) for adjusting an amount of input heat provided to the heat pump (1).